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CHAPTER 4

3D Mobile Data Visualization

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CONTENTS

WE survey the space of three-dimensional mobile visualizations, that is, 3D abstract or spatial data on mobile 2D displays, or mobile head-mount augmented- and virtual-reality displays. As a playful "case study" we use a scenario from the film "*Aliens*," in which a mobile, small-screen visualization device is used to track the movements of enemy aliens around a group of space marines. In this scenario, the marines are overrun by aliens in the ceiling, as their device fails to show them the height dimension of the space around them. We use this example to illustrate how different mobile and 3D interaction techniques could have prevented the misunderstanding in the movie, using both hypothetical descriptions of the improved movie action and a scientific discussion of these scenarios and their implications.

4.1 INTRODUCTION

It could be argued that we live in "Flatland" [1] because we are typically confined to the surface of the planet. Many of our interactions with the world are largely two-dimensional: we move and navigate on a largely two-dimensional plane (considering typical scales), when we place physical items they rest on 2D surfaces, and we read and write text on 2D canvases (i. e., paper), just to name a few examples. Nonetheless, there are certain situations and scales when we have to embrace 3D space. For example, people who go scuba diving suddenly find themselves in a truly three-dimensional world. Similarly, airplane pilots also face the challenge of having to navigate 3D space while surgeons and mechanical engineers also work with 3D structures. With respect to the subject of this book's focus of mobile visualization, there are numerous domains in which the produced data has an inherent mapping to 3D space. While these may be considered to be niche applications within the space of visualization applications (i. e., since a typical person is less likely to encounter them), the ability to explore certain datasets in their native 3D space is essential to a sizable number of experts. Some example data domains where 3D spatial structure is important include:

medical applications where data needs to be represented and understood within the 3D context of the human body;

biological and chemical applications for which the scale can be very small, at the cellular or the atomic level;

engineering applications where the underlying 3D structure comes, e. g.,from a building information model (BIM) or computer aided design (CAD), Figure 4.1;

geography or geology where the structure is the earth's crust or some other aspect of the physical world, Figure 4.2;

astronomy or astrophysics applications where the structure extends beyond the world to the various scales of space.

In this chapter we explore how mobile computing and display technologies, existing and emerging, can be used to explore such data particularly taking advantage of these devices to provide a live window onto these 3D structures. For this purpose we take a rather broad view of what it means to have a *mobile* visualization, embracing aspects of being able to move the displays, move our heads with head-mounted equipment or even with respect to static stereoscopic screens, and if the 3D visualization subject moves in space with respect to a screen (also see the discussion on the definition of mobile visualization in Chapter 1). However, first we motivate the discussion considering both the need for, but also the challenges facing 3D mobile data visualization.

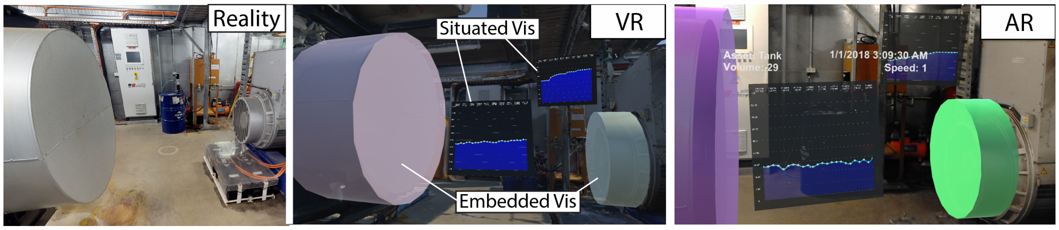


Figure 4.1: Integration of time-series (in this case energy consumption by HVAC systems), and CAD model data into a physical building with both VR and AR views to support different scenarios. Images taken with the Corsican Twin system [69].

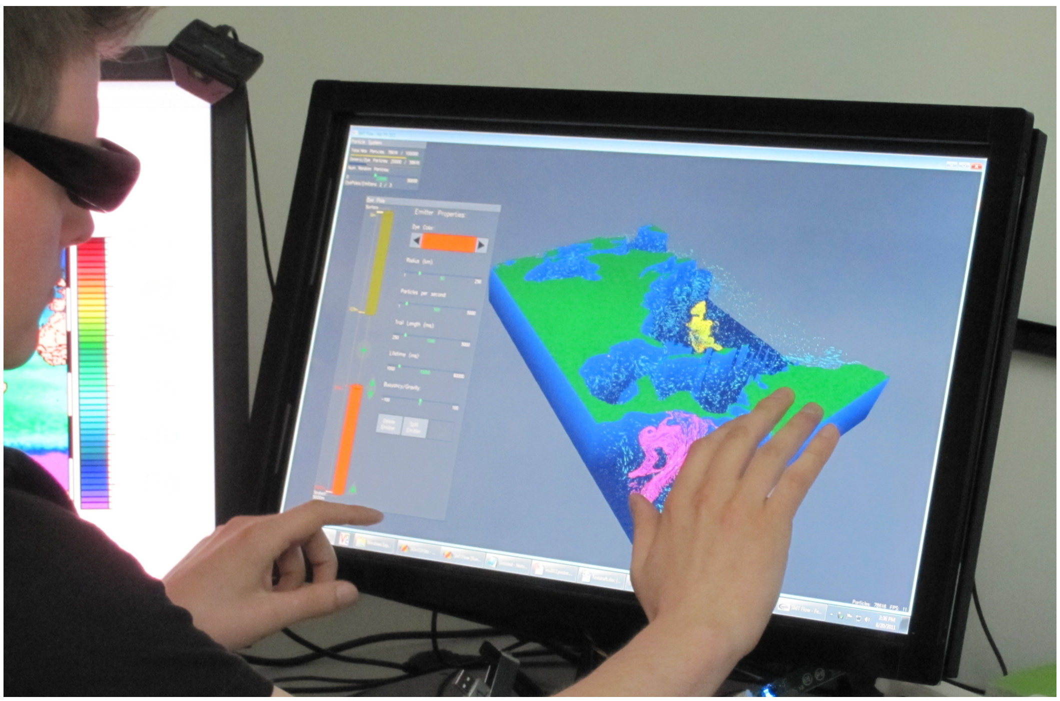


Figure 4.2: Example of a non-mobile ocean flow visualization supported by multi-touch interaction in 3D rendering [17]. *Image © Thomas Butkiewicz, used with permission.*

4.2 NEED FOR 3D MOBILE DATA VISUALIZATION

In Section 4.6 we introduce a design space for 3D mobile data visualization which considers “3D-ness” across three perspectives: *data*, *device* and *representation*. We define these perspectives more formally in that section, but it is already useful to consider the examples of domain specific data above in these terms in order to identify opportunities for 3D mobile visualization.

Medical imaging—such as CT scans or X-rays—gives rise to 3D volumetric data. An opportunity for augmented reality is to provide a doctor with a view of this volumetric imaging ‘spatially-anchored’ in the context of the patient’s body. For example, to precisely locate a foreign body or tumor and potentially to guide surgery.

In such a scenario, a hands-free device such as a headset, is desirable to leave the surgeon's hands free to operate.

Electron microscopy or simulation gives rise to volumetric data of biological or chemical substances and processes. However, they are not typically anchored in a useful spatial context. Here, virtual reality (VR)—decoupled from the viewer's surrounds—might be a more appropriate medium for visualization.

The engineering applications examples we mentioned may be spatially anchored, for example in built infrastructure. It may be useful for site workers to visualize this in-situ with AR, or it may be more useful in a design context, or in the case where the engineer needs to view the model in miniature, to explore this visualization in virtual reality, from the safety of an office for instance.

Geography and geology is similar to engineering, in that the geo-spatially anchored data may need to be viewed in context when the viewer is on site, or in isolation when it needs to be considered holistically. The same thing applies to astronomy: a casual viewer may want information about the night sky as they look at it, while an astronomer may be interested in galaxy scale visualization.

To summarize, some data scenarios are best understood in a situated way, that means we see the visualization at the location to which it refers. If the reference location is in the world, we define such data as being *geo-spatially anchored*. In the medical example, the reference space against which the data is *spatially anchored* is the patient's body.

Seeing data in its spatial context is not the only reason why mobile visualization devices capable of 3D are useful. Engineers may need to look up the CAD model for an entire site while out of the office. A portable VR capable device would be helpful in this scenario to enable data exploration on the go.

Increasingly, dedicated immersive devices become available that were specifically created to be used in a mobile fashion. At the consumer end, Google Cardboard[1] pioneered the notion of a simple holder and lenses to turn a modern smartphone into a VR headset. For professionals, commercial AR systems like Microsoft HoloLens are fully self-contained computing devices with dedicated graphics and computer vision hardware to provide stable augmented reality data overlays. These devices represent opportunities for new applications for 3D mobile data visualization that will permeate the way we work or potentially, our personal lives, as discussed in Section 4.9.

4.3 PROGRESS TOWARDS 3D MOBILE DATA VISUALIZATION: A MOVING TARGET

At the time of writing, mixed-reality technology has been under development in research labs for a long time. The term was coined in 1994 by Milgram and Kishino [58] to describe multisensory blending along a continuum between virtuality and reality. In recent years advances in the underlying technologies (such as display resolution, graphics rendering capability, tracking, but also optics) have made wearable headset technology seem tantalizingly close to commercialization. A number of very highly

[1]https://arvr.google.com/cardboard/, accessed January, 2021

touted startup companies have delivered products (e. g., Meta[2], Daqri[3]) but have ultimately failed to recoup on very significant startup funding, due to a number of factors. Mixed reality (MR) encompasses a broad range of technological solutions with heterogeneous levels of development or commercial success: virtual reality (VR) has, for instance, attracted more attention, and achieved more technological advances and commercialization (e. g.,Oculus Rift[4]) than augmented reality (AR). Technology immaturity still remains a significant challenge across the mixed reality continuum: headsets remain cumbersome, much less powerful than desktop computing environments, and aspects like field of view, natural hand gesture and voice interaction have remained disappointing even in recent devices. These remaining problems, it seems, still require significant research and development.

Despite the technical challenges facing practical deployment of MR into real-world applications, there are still some organisations with very deep pockets pushing the technology forwards. Close to deployment but still ironing out problems, the US military has probably the most sophisticated AR system in the F-35 plane's Helmet Mounted Display System (HMDS) [64]. The HMDS uses the significant computing and sensor resources of the plane to give the pilot a seamless view of important information around the plane, such as the positions of targets, even *through* the opaque floor and walls of the cockpit. Microsoft and the US Army have signed a very significant contract to adapt its Hololens headset technology to a device incorporated into soldiers' helmets [36]. Similar in intent to the F-35 HMDS, this project aims to provide situational awareness to soldiers in the field via mixed-reality. However, since such a headset needs self-contained computing resources and may need to operate in more challenging environments, this project is further from practical deployment.

4.4 MOTIVATING USE CASE

There is a strong tradition of Human-Computer Interaction researchers taking inspiration from science fiction. A recent survey [42] found 137 references to science fiction by 83 papers from the ACM CHI conference's proceedings to 2017. It is also not without precedent for information visualization researchers to cite science fiction as a source of inspiration. For example, Elmqvist et al. [29] cite the film Iron Man 2 as an example of fluid interaction for immersive data analytics. In the Iron Man universe, holographic imagery blends seamlessly into the characters' world and effortless interaction with that imagery using "magical" technology enables impressive data analytics to relentlessly drive Tony Stark's genius-level insights. Such depictions of mixed-reality go well beyond the limitations of current technology. They are closer to virtual-reality pioneer Ivan Sutherland's [83] 1965 concept of an "Ultimate Display" (one which makes the virtual and real indistinguishable). This was a thought experiment on the theoretical possibilities of the technology, rather than something we might critically analyze and practically learn from in terms of usability.

While fun and inspiring to watch, it is difficult to relate such fanciful scenes as

[2]https://en.wikipedia.org/wiki/Meta_(company), accessed January, 2021
[3]https://en.wikipedia.org/wiki/Daqri, accessed January, 2021
[4]https://en.wikipedia.org/wiki/Oculus_Rift, accessed April, 2021

those of films like Iron Man[5] back to what might be realistically achievable for mobile data visualization with foreseeable technology. We therefore take a slightly different approach. We introduce our discussion in this chapter with a look at an older science fiction film that posits a mobile data visualization scenario. It is interesting in that the film's vision predates the current wave of mixed-reality technology and related enthusiasm. In fact, the "future technology" depicted looks rather achievable—even primitive—compared to mobile-screened devices now in everyday use. Arguably, it presents an industrial, in-the-field, use-case not too dissimilar to those likely being considered by Microsoft and the US Army. After describing the scene as it was originally presented using technology that we might now consider mainstream, we ask the question: with mixed-reality 3D data visualization, would this scene have played out differently?

4.4.1 An Example: *Aliens*

The film *Aliens* was released in 1986. Depicting a rescue mission by a team of "colonial marines" of a human colony in distress on an alien planet, it is clearly futuristic. Yet its depiction of technology is a product of its time. The scene we focus on begins at 98 minutes and 25 seconds into the film.[6] A team of marines led by Corporal Hicks and accompanied by a level-headed civilian (Ripley) has already survived terrifying encounters with the Alien "Xenomorph" creatures. They are in the process of barricading themselves into a room, PFC Vasquez welding the door shut to keep the creatures at bay. Key to the scene is a piece of mobile data visualization technology being wielded by PFC Hudson, a "tracker" which uses ultrasound to detect motion nearby.[7] The source of motion is depicted in a top-down radial display on a small 2D screen on a handheld device.

The scene is depicted in Figure 4.3. The synopsis is as follows [21]:

> HUDSON: Twelve meters. Man, this is a big #@$%ing signal. Ten meters.
> RIPLEY: They're right on us. Vasquez, how you doing?
>
> *Vasquez is heedlessly showering herself with molten metal as she welds the door shut. Working like a demon.*
>
> HUDSON: Nine meters. Eight.
>
> RIPLEY: Can't be. That's inside the room!
>
> HUDSON: It's readin' right. Look!
>
> *Ripley fiddles with her tracker, adjusting the tuning.*
>
> HICKS: Well you're not reading it right!

[5]Star Trek's holodeck is also a classically cited mixed-reality "MacGuffin" (the movie trope of an artifact that exists just to drive the plot), e. g., [54]. Arguably, the Holodeck has inspired a great deal of mixed-reality research and created resonance for technologies like CAVE.

[6]*Aliens*Ceiling Scene on YouTube: https://www.youtube.com/watch?v=1bqSgvEZNtY, accessed January, 2021

[7]The M314 Motion Tracker: https://avp.fandom.com/wiki/M314_Motion_Tracker, accessed January, 2021

Figure 4.3: A high-consequence failure of a mobile visualization device to correctly convey the 3D structure of data—from the film *Aliens*. *Image © Magdalena Boucher.*

HUDSON: Six meters. Five. What the #@...

He looks at Ripley. It dawns on both of them at the same time. She feels a cold premonitory dread as she angles her tracker upward to the ceiling, almost overhead. The tone gets louder.

Hicks climbs onto a file cabinet and raises a panel of acoustic drop-ceiling. He shines his light inside.

At this point the team discovers that they have been overrun by the alien swarm which advanced through the ceiling. Lacking a representation of the third, vertical dimension their 2D device gave them no forewarning. They make a frantic retreat and several lives are lost in gruesome fashion.

4.4.2 Analysis of the Example: Different Kinds of Mobility

The example mentioned above led to human casualties in the movie because the situation at hand was actually quite complex and the visualization of the data not particularly suited for it. Several components contribute to the complexity of the situation.

The first challenge is that the data to be visualized—the positions of the incoming aliens—is inherently three-dimensional and needs to be mapped appropriately to be understood correctly. The visualization of spatial 3D data has unique challenges due to problems such as occlusion [75] (in particular on classical, non-stereoscopic displays) or the need for appropriate interaction techniques that may or may not mimic real-world interactions [4, 9, 82, 90]. This first challenge can be addressed by using 3D rendering together with suitable stereoscopic display hardware to create environments like those we are used to in our daily lives.

A second challenge in our motivational scenario is the issue of *mobility*: many things are happening and can happen at the same time yet at different places, and the visual representation should be updated to account for the movements of all the actors in the scene. The first actors are the moving aliens whose positions need to be updated. Nothing there is particularly challenging as long as the employed sensors track the aliens precisely and responsively. Nonetheless, the positioning of the visual representation might have to be adjusted accordingly as well, which begs the question of whether the (stereoscopically shown) visual representation itself is mobile or not: it can change its position with respect to the mobile device/display and to the world itself. The second set of actors are the humans and the devices they are holding or wearing. They too are mobile in 3D space and the representation should account for this mobility.

Overall, we can then distinguish different types of mobility with respect to the viewer, the display, and the visual representation to characterize different mobile 3D visualizations (see also Chapter 1):

- *mobility of the user*: the user can be mobile or (more or less) static in the 3D world as well as with respect to the device providing the visualization,
- *mobility of the display device*: the display itself may be static with respect to the world reference frame or with respect to the user('s vision), and

- *mobility of the visual representation*: the visual representation can be fixed or mobile with respect to the 3D world or the device that displays the visualization.

Characterizing 3D mobile visualizations with these dimensions facilitates understanding what kind of information is available at what moment as well as how to interact with the visualization in order to obtain more insights.

4.5 CHALLENGES OF 3D MOBILE DATA VISUALIZATION

While Section 4.1 outlines opportunities for 3D mobile visualization and promises the imminent availability of devices capable of realising these opportunities, many challenges remain which may impede the uptake of this technology in many situations. Some of these challenges are directly visible in our motivating example. Nonetheless, these challenges represent opportunities for researchers to make impactful contributions to the field. We now detail some of these challenges.

A new interaction paradigm. One obvious challenge is that mobile 3D computing environments offer very different modes of both display and interaction to traditional desktop computing environments. Thus, much of what human-computer interaction researchers have learned about desktop computer interaction since the 1960s may need to be reassessed or reinvented to support natural immersive interaction. In more recent times, touch-computing has been studied extensively as phones and tablets have become many peoples' primary digital devices. While 3D interaction techniques on mobile devices have been extensively studied (see, e. g., existing surveys of 3D interaction or selection techniques [2, 40]) to select and manipulate pre-defined objects, these techniques are unlikely to translate to 3D data visualization scenarios in which datasets do not present such pre-defined features or structures (see [11]). Similarly, interaction with data visualizations has now been extensively explored in all of these contexts, but similar effort may be required to realize natural and effective data visualization in immersive environments [11, 13]. A survey of many relevant interaction techniques for 3D mobile data visualization can be found in the report from Besançon et al. [11] who classify approaches based on the visualization tasks they help achieve, the interaction paradigm used and the supported output devices. Finally, if we want to use 3D data visualization in a mobile context with limited resources, we need ways to transition from traditional desktop/workstation-based data analysis/data storage to a mobile analysis/data access, and back [91, 92].

Integrating data and environment views. In general, a lot of the scenarios for mobile data visualization considered in this book involve devices being carried through the world, and the particular location of the device in the world is important context for the visualization. The location of the device and other objects or data in the 3D world around the device are therefore important pieces of context which must be accurately displayed to the user. There are many ways in which this kind of spatio-data coordination can be achieved, including ways that developments in technology, such as spatial tracking and immersive displays, are only now making viable. Devices like smartphones have long had location services which are adequate for applications requiring knowledge of the position of the device to tens of meters. Examples of such applications include turn-by-turn navigation, or the kind of *in-situ* geographic or geological survey data visualization scenarios described above. But devices which can use, for example, on-board cameras to locate themselves to centimeter accuracy are a much more recent development. Commercial software development kits providing accurate 3D location services based on camera, accelerometer and compass sensors in commodity phone and tablet devices started appearing about 2009 [47]. Such accurate positioning in all three spatial dimensions, as well as accurate orientation tracking, makes the above-mentioned "window on the world" data overlay for handheld devices scenario a possibility. It also enables wearable headset devices to more seamlessly introduce data overlays onto the wearer's field of view. Whether with headsets or handheld devices, such overlay of virtual data onto the world, is referred to as *Augmented Reality* (AR). As headsets improve and provide more seamless mixing of the virtual and real worlds the term *Mixed-Reality* (MR) is becoming more common.

Another challenge implicit in many of the example domains above is integrating visual overlays with the environment [71]. For example, for handheld AR the screen of the device may function as a window onto the world that overlays the physical world as the user moves the device in front of their field of view. The handset obstructs their actual view of the environment, but lowering the device easily allows the viewer to recover an unobstructed view. Headset AR provides a similar "data window" on the world, but with the additional challenge that the user cannot so easily remove the display from their field of view. We cannot control the environment. We cannot ensure that it is a safe place to stop and explore data. How can we show information and data without obstructing people's vision or distracting them from avoiding running into static obstacles or dodging objects moving towards them in the environment? We must design displays that can adapt, for example, placing data graphics to one side of important objects or against blank areas of the scene.

Physical scale. The scale of the underlying spatial data may be significant when considering applications of mobile data visualization. This is because the scale of the data being similar to, or radically different from the scale of the display of the device being used to visualize that data, may have significant implications on how the device can be used to explore the data. The engineering example above highlights this challenge. How do we view a CAD model that is bigger than the room in which an engineer is standing? How do we reconcile an overview of the whole building site with detail at the location that the worker is examining? If the geo-spatial data needs to be presented in the context of a map of a large area around the user (as perhaps may be used by a geologist in a field survey) then it may be important to represent the device's location relative to the map. At the extreme scales of atomic or astronomical data, the representation must be much more decoupled from physical space and the spatial mapping may be more abstract for convenience.

Computational and hardware challenges. Apart from the physical scale of data, another type of scalability issue is the computing challenge of dealing with very large (as in quantity) data. Many 3D volumetric datasets are huge: scaling cubicly with the dimensions of the volume under consideration. There is both an algorithmic challenge in dealing with such data efficiently, but also a hardware challenge. Mobile devices are limited in their computational, visual, and power/battery fidelity compared to 3D rendering workstations. The massive market for smartphones has been a strong driver of steady improvement against these limitations, but further innovation is needed. For visualization, improved display technology is critical. A research challenge for immersive displays is providing true depth of field. For example, the so-called *vergence problem* causes discomfort when a headset display presents an entire scene in focus, rather than allowing the wearer to naturally focus their eyes on objects at different depths. Experimental "light-field displays" use multi-layer LCD screens to render true depth of field [41], but these have yet to be successfully deployed beyond laboratories.

Abstract versus spatial data and spatio-data coordination. Three-dimensional structures can also be important to represent data that does not have a physical spatialization. Examples of such *abstract* or *non-spatial* data visualization include visualizing changes in any two-dimensional dataset over time. Such time-dependent 3D data visualizations are typically called "space-time cubes" [3]. An example of a space-time cube representation of abstract data might be a visualization of stock trade price versus volume over time. 3D abstract data visualization is also applicable when the relationships between any three quantitative, ordinal or categorical dimensions need to be viewed equally against each other. In these scenarios, the mapping of the data to space around the user of the mobile data visualization may be arbitrary or metaphorical, but doing so may make sense if it provides a natural way—using the capabilities of the mobile data visualization device—to explore that data. Following Cordeil et al. [26] we refer to this mapping of the data visualization space to the space of interaction around the user as *spatio-data coordination*.

Co-located collaborative contexts. While immersive co-located collaborative scenarios of immersive visualizations are very promising [53] and used for other purposes such as design work (e. g., [65]), a survey of collaborative work in augmented reality [74] has highlighted that only very little work has considered such scenarios and its challenges. Yet, some interesting problems should be studied in that context: how to distinguish between public and private view points (especially when using a separate device as interaction proxy, e. g., [73]), how to best convey collaborator internal state and private or public interaction, or how to handle undo/redo actions on the publicly shared views are fundamental issues that have not yet been addressed for immersive collaborative visualization contexts.

Human and organisational barriers to adoption. Not all barriers to practical use-cases for mixed reality are technological. There are also significant organisational and environmental concerns that may impede adoption of mixed-reality technologies into work-place scenarios. Masood and Eggar [56] develop a model designed to help predict success of AR applications given particular challenges in a given scenario. However, many of the concerns outlined in this model, technological, organisational or environmental, are becoming more understood and most can be reasonably expected to be overcome in the medium term—though whether this happens in five years or 20 years is still difficult to predict. The point is that understanding the full potential of mixed-reality, and the kind of impact it may be able to achieve for applications like data visualization, remains a speculative activity.

The playful speculations we engaged in through Section 4.4 and some of the challenges we have just explored help set the agenda for a more traditional survey of techniques and applications for 3D mobile data visualization, as well as some theoretical contributions in the form of a design space for 3D mobile data visualization.

4.6 A DESIGN SPACE FOR 3D MOBILE DATA VISUALIZATION

In order to provide a more systematic view of 3D mobile data visualization, we consider relevant aspects from three main perspectives: data, device, and representation (see Figure 4.4 for an overview of the design space).

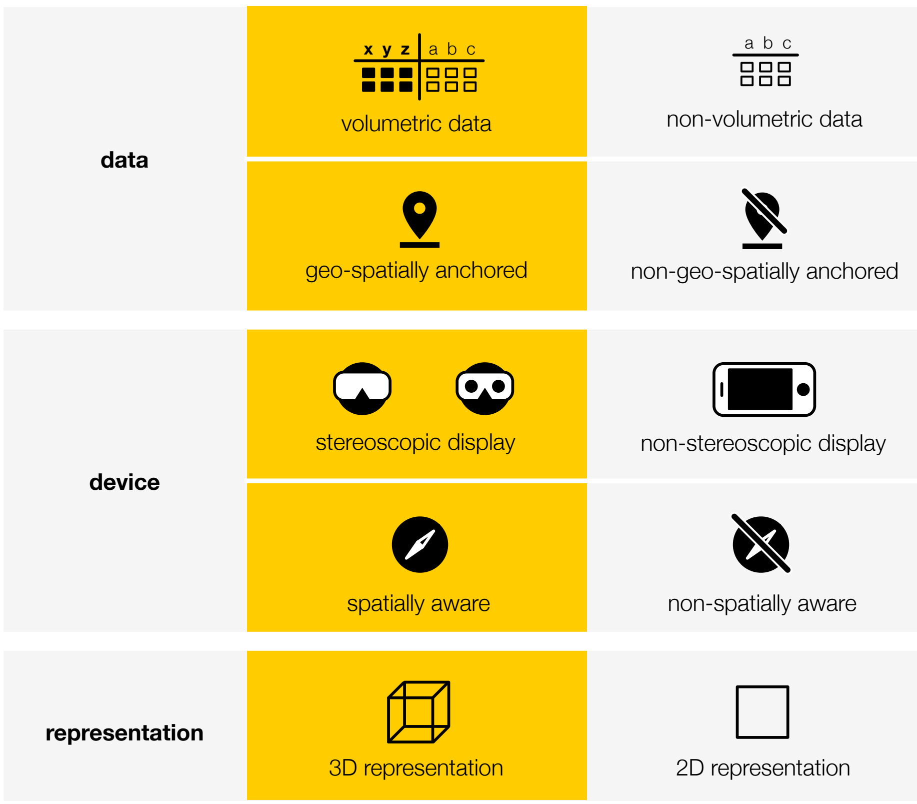


Figure 4.4: Design space of 3D mobile data visualization. In this chapter, we focus on the aspects marked in yellow (left column). *Image courtesy of Wolfgang Aigner* (CC BY).

Data. Obviously, when talking about data visualization, data is the basis for all further considerations. Different types of data lend itself to different visualization techniques for their graphical representation. Therefore, different kinds of data and their characteristics are considered in visualization in general [60, 85]. In the context of 3D mobile data visualization, two relevant aspects come to play. First, we can distinguish whether the data itself encodes 3D geometry (*volumetric data* that is inherently spatial such as the construction plan for a wind turbine) or not (*non-volumetric data* such as wind measurements). Second, data might be directly related to

3D space or not. An example for *geo-spatially anchored* data are wind measurements at different geo-spatial positions, areas, or volumes. *Non-geo-spatially anchored* data lack such a positional relation and are more abstract, as for example stock market data. For spatially anchored data we consider both, data connected to absolute positions in 3D space (**geo**-spatial anchoring, e. g., the mentioned wind data) as well as data connected to relative positions in 3D space (spatial anchoring, e. g., medical 3D scans related to certain body parts of a patient).

Device. From a device perspective, we can differentiate between *stereoscopic display* where a true 3D impression can be created for the human user and *non-stereoscopic display* where only 2D projections can be rendered. Typical examples for stereoscopic displays are VR headsets like the Oculus Quest or HTC Vive, AR headsets like Microsoft Hololens or Magic Leap, but also CAVEs or shutter glasses used in 3D movie theaters. Besides that, non-stereoscopic displays are also relevant in the context of 3D mobile data visualization. Examples are tablets and smartphones but also smartglasses like Google Glass or Epson Moverio. In addition to stereoscopy, spatial awareness is a relevant aspect to consider. *Spatially aware* devices are able to relate their display to the 3D space around them. For instance, AR devices, like the Hololens, include different kinds of sensors to recognize its surroundings and can attach a virtual item to a wall or physical object in the field of view. *Non-spatially aware* devices lack this capability and are thus more detached from the real-world physical context. Note that devices for all four possible combinations of stereoscopy and spatial awareness exist and both stereoscopic and non-stereoscopic displays might be spatially aware. For example, while a smartphone (handheld AR) might be spatially aware, a VR headset like the HTC Vive might not be.

Representation. Independently from the stereoscopic ability of devices, visualization methods can either employ three-dimensional or two-dimensional visual primitives. *3D representation* uses 3D geometric objects, e. g., for volume visualization or in a 3D bar chart. *2D representation* applies 2D shapes such as points, lines, or areas, e. g., for drawing a treemap or regular bar chart.

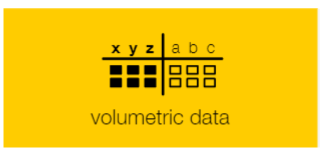
Focusing on the perspectives presented above allows us to emphasize the aspects that are most relevant to 3D mobile data visualization. Specifically, we unpacked the aspect of '3D' which is multi-faceted and might be related to data, the device, or the representation. With the presented design space, we have a tool that lets us describe what needs to be taken into account more precisely, characterize available approaches more systematically, and point out challenges and areas that need further research.

We consider methods, technologies, and techniques relevant for 3D mobile data visualization if at least one (and often more) of its aspects fall into a category of the left (yellow) column (see Figure 4.4). Bear in mind that most of the theoretically possible combinations of the five mentioned design aspects make sense and can be found in concrete examples. This leads to a wide variety of possible approaches and clearly shows the complexity of the topic. To structure our chapter, we have identified the most relevant configurations of the mentioned design space aspects. In the following sections, we provide an overview of the available approaches and discuss their specifics.

4.7 EXPLORATION OF RELEVANT CONFIGURATIONS OF OUR DESIGN SPACE

In this section we explore relevant applications of the design space we previously explored. We focus particularly on configurations that align with our definition of 3D mobile data visualization in this chapter, in other words approaches that satisfy at least one of the following: the data is volumetric, the data is geo-spatially anchored, the display is stereoscopic, the display is spatially aware, the representation of the data is 3D (see Figure 4.4). We structure this exploration into two main categories by data and display type: Volumetric data on non-stereoscopic displays (Section 4.7.1); Volumetric data on stereoscopic displays (Section 4.7.2); and Non-volumetric data on stereoscopic displays (Section 4.7.3).

4.7.1 Volumetric Data on Non-Stereoscopic Displays



Classical non-stereoscopic displays (for instance desktop monitors, mobile phones, or tablets) can represent volumetric data using a projected 3D representation. Popular 3D-based applications such as Fusion 360 from Autodesk,[8] or VTK with Kiwiviewer[9] have mobile versions of their 3D tools. In addition, platforms such as Unity[10] or the Unreal Engine[11] also made development of 3D applications on mobile devices easier in the last couple of years.

Classical 3D representation on non-stereoscopic mobile devices

Apart from the popular CAD softwares on mobile devices, mobile applications have also been developed to tackle the needs of researchers working with volumetric data. Kitware has made their famous visualization tool VTK available and running on mobile devices[12] to support analysis of scientific and medical data on the go.

A lot of past research has focused on the challenges to provide interactive 3D rendering of scientific data on mobile devices, which have a much lower processing power than classical desktop stations, through specific rendering algorithms and techniques (e. g., [62, 63, 72]) while other approaches focused on the possibility of

[8]https://www.autodesk.com/products/fusion-360/blog/fusion-360-mobile-ios-android/, accessed January, 2021
[9]https://www.kitware.com/kiwiviewer/, accessed January, 2021
[10]https://unity.com/, accessed January, 2021
[11]https://www.unrealengine.com/en-US/, accessed January, 2021
[12]https://vtk.org/Wiki/VES, accessed January, 2021

offload the processing/rendering to servers and directly stream from them (e. g., [22, 34, 67]).

Providing interactive 3D representations on mobile devices helps leverage the benefits of these devices within the workflow of domain experts. For instance, 3D representations on tablets or phones can be helpful for medical experts to rapidly select deep brain stimulation settings (e. g., [19]) or easily integrate in the workflow of other researchers (e. g., [8]).

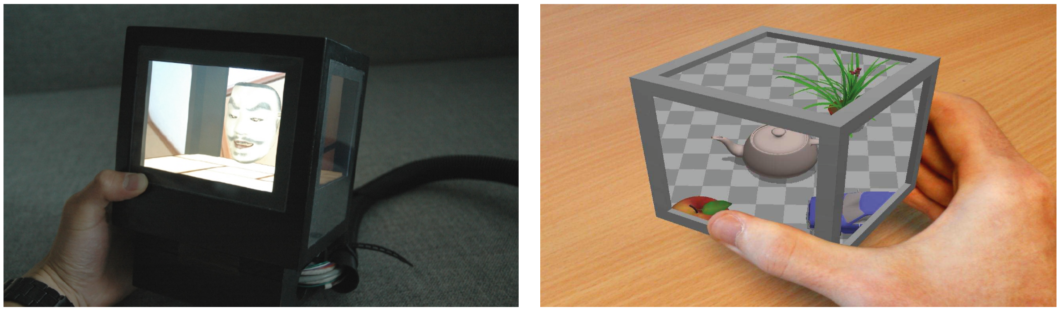
In these classical examples of mobile, volumetric data visualization on mobile devices, users are usually static with respect to the device and the visual representation is static in the 3D reference frame (non-spatially aware). However, users can move around without affecting the visual representation and bring the devices with them. The initial *Aliens* example we studied is a specific example of such visualization but is augmented here with 3D rendering capabilities and interaction. In most cases, such 3D mobile visualization is used in order to benefit from the familiarity that users have with handheld devices such as phones or tablets. This means that most interaction with 3D representations is achieved through 2D touch input on the screen which can be difficult to translate into 3D interactions. Currently, there is no standard way of interacting with 3D representations using touch input [9]. Recent work has investigated the possibility to augment 2D touch input with pressure sensing in order to facilitate mapping to 3D manipulations [90] showing the benefits of such hybrid interactions, but such interaction mappings are still not common for regular users.

Coming back to our *Aliens* motivating example, we could easily imagine that the mobile device the team is using could display a proper 3D rendering of the vessel that would show the 3D positioning of the aliens. We could envision that casualties could have, therefore, been avoided. However, one also has to consider in this case that the marines would have had to identify on which floor the aliens were which might have been difficult on a full model of the ship they are in. This would have therefore required interaction to navigate the model and identify the precise location of their enemies, which, with only 2D touch input could have taken a long time [9].

The *Aliens* scenario might have been slightly better when considering spatially-aware devices. With spatially-aware devices, users can directly manipulate the device in order to interact with the 3D data projected on the screen. In this case, the mobile device acts as a tangible interface and users are able to manipulate the visualized data [8, 32, 76], manipulate a cutting plane to understand the internal structure of the data [8, 23, 77, 78], perform 3D selections and annotations [10, 23], or manipulate specific tools to better understand the data [8]. In most cases, tangible interaction is combined with the touch screen to provide hybrid interactions. If we consider the marines scenario, such hybrid interaction can potentially help navigate through the different levels of the 3D model of the spaceship in order to identify more quickly where the aliens are which might have saved the marines.

Fishtank VR

A first exception to the classical 3D projection on a non-stereoscopic display is the one of Fishtank VR applications [59, 93], see Figure 4.5. They provide head-coupled



(a) (b)

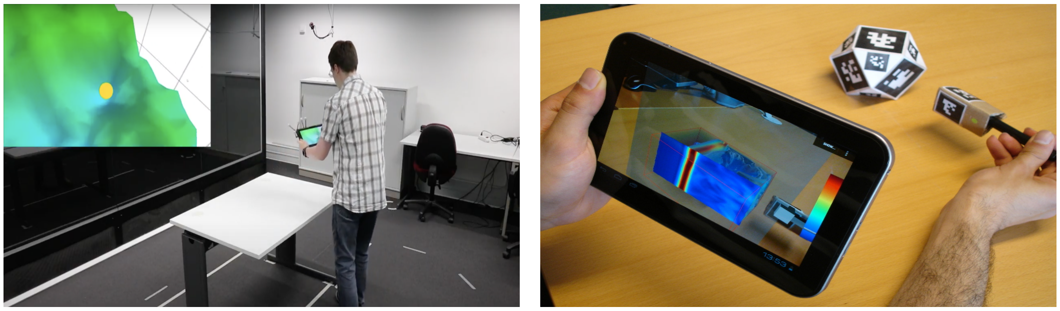
Figure 4.5: Examples of fishtank VR devices. On the left, a 5-face p-cubee [79], on the right an AR simulation of an interactive cubee [37]. *Left image courtesy of Ian Stavness* 🅭🅯*, right image from [37] © IEEE 2014, used with permission.*

perspective projected stereo imaging on a rather small display that is fixed at a specific location. Recent examples of this are portable devices like the *Cubee* [80], its variations (e. g., [33, 79]) and other fishtank devices (e. g., [51]). Other fishtank shapes have also been investigated (e. g., polyhedric or spheric screens [5, 6, 35, 84]). Moving the device around does not have any impact on the visualized world, but the user can look at virtual information from different angles and thus leverage the shape of the device. For this, the user is tracked in order to adjust the view and give them an illusion of looking at 3D objects or data. The user is therefore mobile while the device and the visual representation are static in the 3D world.

Coming back to the *Aliens* scenario, we can easily imagine that such a device would have been useful in order to get a perception of real 3D locations without the use for headset or stereoscopic rendering. However, the location would only be perceptible by one user at a time and might require them to position themselves awkwardly such that they might not be in the best posture to defend themselves. In addition to these limitations, the one marine who would have had access to the information would have needed to then transmit the information to the others, probably wasting precious time when facing an alien invasion. Nonetheless, one can argue that their odds would already have been greater than in the movie.

Handheld AR

A second exception lies in handheld augmented reality [45, 25, 88, 89, 97], see Figure 4.6. Here, we make use of the handheld device as if it was see-through. The idea is to use the device's camera in order to mirror the real-world behind it and add 3D virtual information on top of it on the screen. In this case the display is mobile in the 3D world while the user is mostly static. The visual representation can either be fixed or mobile: it can on the one hand follow the device's movement and always be visible to the users (non-spatially aware) or stay at a fixed position in order to reflect the 'real' position of the data/object in the 3D world (spatially aware). In practice, these solutions rely often on optical markers tracked by the device's camera



(a) (b)

Figure 4.6: Examples of handheld AR devices used for visualization purposes. On the left, a tablet's spatial movements are tracked to interact with 3D visualization [15], on the right, the tablet or the tangible stylus are used to slice through a volumetric dataset [38]. *Left image courtesy of and Wolfgang Büschel, right image courtesy of and CC-BY Issartel et al.*

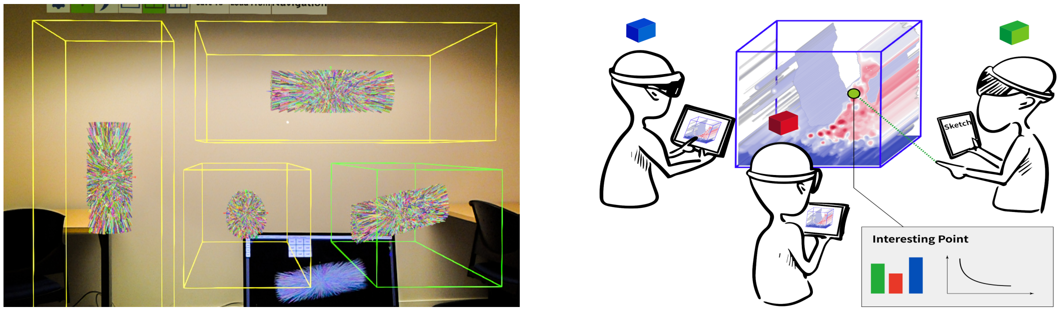
in order to allow data manipulation and exploration [15, 38, 66] although commercial markerless solutions have also been developed, e. g., IKEA Place.[13] Finally, the cubee example mentioned in Section 4.7.1 has also been envisioned as an interactive and spatially-aware handheld VR/AR device [37] displaying data based on its location and allowing users to interact with and select virtual data and objects.

In our *Aliens* scenario, handheld AR devices are an improvement over the static fishtank VR devices. The display being mobile, interactive and potentially spatially-aware removes the problem of awkward positioning. However, the real 3D location of the aliens is still only correct for one user. The odds of all marines surviving the aliens are therefore much higher although the device still needs to be held and might therefore hinder the marine's access to their rifle. The two limitations of this solutions can actually be solved by stereoscopic rendering which we investigate next.

4.7.2 Volumetric Data on Stereoscopic Displays

Due to the nature of the data, stereoscopic rendering is often considered to mean that one visualizes data in a "volumetric" way. The data is not projected onto a 2D screen anymore, but instead can be perceived directly in 3D. Early work on stereoscopic rendering (e. g., [28, 43]) demonstrated the benefits of immersion for volumetric data analysis and understanding. Different environments and devices can realize stereoscopic rendering such as CAVEs (e. g., [28]), stereoscopic screens (e. g., [52]), stereoscopic glasses, or headsets (e. g., [14, 50, 61, 92]). Depending on the envisioned solution, users are more or less constrained in their movements in the real world.

[13]https://apps.apple.com/us/app/ikea-place/id1279244498, accessed January, 2021



(a) (b)

Figure 4.7: On the left, combining a laptop with traditional visualization tools and a Hololens for particle physics visualization [92], and, on the right, using a tablet as a visualization and interaction proxy in AR co-located collaborative analysis [73]. *Image from [92] © ACM, image from [73] © Mickael Sereno, Lonni Besançon, and Tobias Isenberg, both used with permission.*

For example, on the one hand, headsets provide a high degree of flexibility and can, therefore, be particularly interesting for understanding the spatial arrangement of data. Yet, they currently provide a limited field of view. On the other hand, CAVEs, allow users to be immersed in data [70] but do not provide mobility and are rather complicated to set up [7]. The mobility of the spatial representation is also something that has to be considered with stereoscopic rendering: The displayed data can remain static with respect to the user's field of view (non-spatially-aware setting; mobile with respect to the world reference frame). It can also remain static with respect to the world reference frame (spatially-aware setting; mobile in the user's field of view reference frame). In the first case, the virtual position of the data might not reflect its real physical position (if the data are related to real objects or processes) but will provide users with information regardless of their position. In the second case, if the data related to real objects or processes, its virtual position will reflect its real position but users will have to actively navigate the real world in order to see the visual representation of the data.

Modern head-mounted display devices make rendering 3D data in a stereoscopic context a relatively mainstream proposition. It has thus become fairly common activity to provide immersive walk-throughs of architectural and engineering plans. For instance, professional solutions allow clients of architects to explore, walk through, and analyze the results of architectural designs in VR (e. g., Enscape[14] or theViewer[15]). AR in particular is starting to be used in manufacturing to guide workers in assembly tasks [57]. Thanks to computer vision and marker based positioning, overlays can be accurately placed on surfaces to show workers precisely where components should be placed (spatially aware). Both VR and AR are starting to have significant roles in industrial training scenarios.

[14]https://enscape3d.com/features/architectural-virtual-reality/, accessed January 2021
[15]https://theviewer.co/home, accessed January 2021

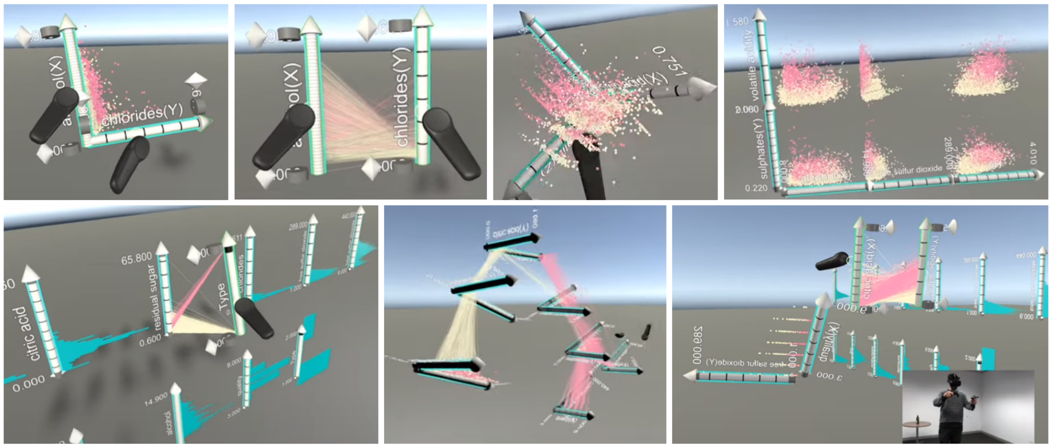
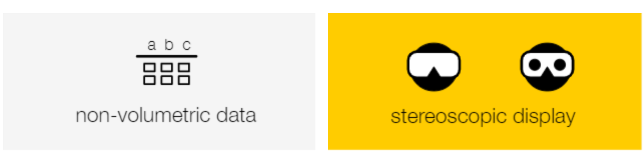


Figure 4.8: ImAxes: Visualizations built with ImAxes by end users in VR [27]. *Image courtesy of and © Tim Dwyer, used with permission.*

Stereoscopic rendering can also be coupled with regular displays. Some researchers created Hybrid Virtual Environments (e. g., [50, 73, 91, 92]) that combine several output devices together (and often also several input devices) to benefit from the advantages of immersion and the traditional 2D analysis tools available on classical devices, see Figure 4.7.

In our *Aliens* scenario, having access to stereoscopic and spatially aware renderings could have proven to be extremely useful to the marines. If we consider that the visualization was designed to follow the positions of the aliens, the marines could have easily identified the data points representing the creatures but would have had to pay attention to check in every direction until they actually found out their physical location. The virtual overlay might have made aiming at the invaders slightly more difficult but casualties could have probably been avoided.

4.7.3 Non-Volumetric Data on Stereoscopic Displays



In this section, we focus on non-volumetric data that do not encode 3D geometry by itself. Albeit such data might not seem to lend itself well to be represented by a 3D visualization, such presentations can be beneficial to the user (e. g., [12]). Particularly in traditional information visualization research, which focuses on 2D representation on non-stereoscopic displays, 3D representations are viewed very critically due to perceptual issues that make perception and interaction more difficult than with 2D representations [60]. Main issues put forward in this regard are depth perception and occlusion. However, when mobile, stereoscopic displays are being used, these disadvantages can be mitigated and further opportunities can be harnessed which cannot be provided in 2D representations [12, 55]. First, depth perception taps into our experience of perceiving the real world around us, where we are constantly taking depth into account through stereoscopic vision. Second, with the mobility of stereoscopic displays (e. g., HMDs) occlusions can be untangled more directly and intuitively by moving in space. Third, co-located collaboration is easier, as physical space can act as common shared display space within which analytical tasks can be performed. And fourth, in case of AR, (objects in) physical space around the viewer can be used as concrete external anchors for information to enhance cognitive processing [49]. This means that, albeit the data itself might not be geo-spatially anchored, it can still be virtually attached to physical objects for spatially aware displays.

Based on the kind of immersive technology used, available methods can be grouped into spatially aware and non-spatially aware approaches. An example for non-spatially aware approaches is the work of Cordeil et al. [27] who developed a system called *ImAxes* to interactively construct axes-based 3D visualizations in VR. Axes can be combined and configured by the end users to create novel visualizations (see Figure 4.8) in the form of coordinated 3D charts. In addition to the work on the design, interaction with, and authoring of data visualization techniques in VR, the topics of storytelling and effects of immersion are highly relevant due to the special characteristics of such immersive environments. In this context, Ivanov et al. [39] present a quite different approach of a VR-based immersive visualization environment with a focus on storytelling and emotional immersion. In their work, metaphor graphics and unit visualizations are used to communicate engaging experiences into statistics of mass shooting victims for example. Avatars represent humans and users can interact with these avatars directly to get personalized stories from the avatars.

In addition to the fully virtual experiences discussed above, Filho et al. [31] introduce the *VirtualDesk*, a VR-based display and interaction metaphor that interweaves VR and physical space. The user sits at a desk wearing a VR HMD and is thus also able to benefit from tangible feedback of the real table (see Figure 4.9).

Going one step further, the physical environment around a user might not only be used to provide haptic feedback and foster situatedness, but also visually. I.e., reality and virtual visualization environments can be interwoven in form of augmented and mixed reality approaches. In their work on AR graph visualization, Büschel et al. [16] display abstract, 3D node-link diagrams in the context of real physical space. The main contribution of their work was an empirical study to compare different options for edge styles. For collaboratively analyzing multi-dimensional data, Butscher et al. [18] developed *ART* (Augmented Reality above the Tabletop) that shows a 3D parallel coordinates visualization anchored on a tabletop (see Figure 4.10).

An even more concrete approach of combining physical space and visual representations has been put forward by Chen et al. [24]. MARVisT is an authoring system for glyph-based visualization in mobile AR. Figure 4.11 shows an example of placing stacks of virtual sugar cubes next to drinks the data is related to. In contrast to most of the approaches presented so far, that focus on visual data exploration, MARVisT has a strong authoring component that allows for the creation of visual representation in an immersive environment. Another approach combines mobile devices and AR

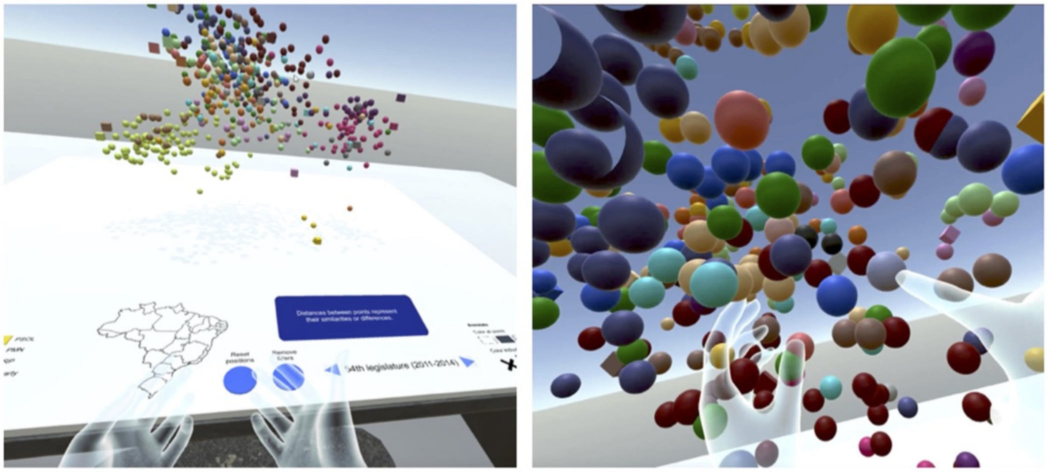


Figure 4.9: VirtualDesk: Projected multidimensional data are shown as 3D point clouds. *Images © 2019 IEEE, reprinted, with permission, from [31].*

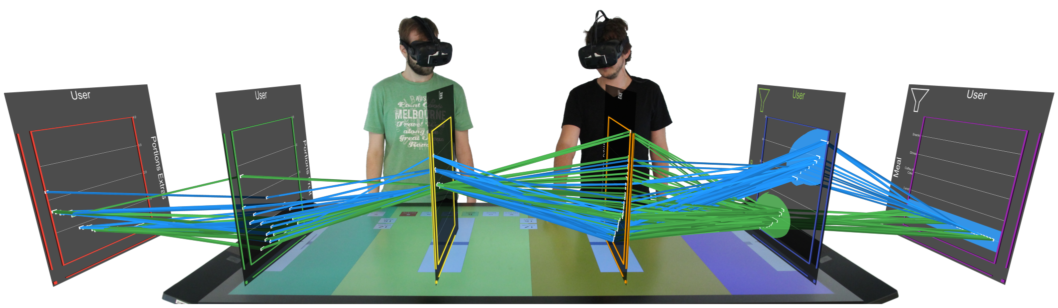


Figure 4.10: ART: Augmented Reality above the Tabletop—a 3D parallel coordinate plot that utilizes 2D scatterplots instead of 1D axes to collaboratively explore multidimensional data [18]. *Image © Simon Butscher, Sebastian Hubenschmid, Jens Müller, Johannes Fuchs, and Harald Reiterer, used with permission.*

headsets to augment 2D mobile visualizations with 3D components on and around the devices [46].

In the *Aliens* scenario, we could imagine abstract representations of captured data about the intruders or about their own resources being shown right next to stereoscopic views of 3D data, allowing the defenders to quickly switch between the two views without the need to refer to external, stationary screens. They could thus keep their focus on the aliens and, with head-worn display equipment, even have access to their weapons.

Geo-spatially anchored data on spatially aware devices

For many data-driven tasks, like repairing a manufacturing machine or conducting a site visit to understand the existing conditions of a physical site, visualizing data in its original environmental context brings benefits to fulfil the task. Visualization

Figure 4.11: MARVisT, a Glyph-based AR representation of the sugar content of drinks that places stacks of virtual sugar cubes next to drinks the data is related to. *Image © 2019 IEEE, reprinted, with permission from [24].*

Figure 4.12: SiteLens: Non-stereoscopic display of air quality measurements (non-volumetric, geo-spatially anchored data) using 3D representations in an outdoor environment [94]. *Image © Sean White, used with permission.*

methods that deal with linking of data to their origin are also referred to as "situated visualization" [96]. Related to our design space, we are focusing on geo-spatially anchored data in this section.

For connecting the representation to the physical context, the approaches presented are usually spatially aware. Such overlays of virtual elements on top of the physical environment can however be challenging. First of all, the visuals should not occlude real-world elements. Several parameters therefore have to be taken into account: the size of the visuals, their positions, and their transparency. Then, the design of the visual should be compact and complementary to the real world so that it would not stand out too much and potentially take away the users' attention constantly. Finally, visuals should be properly linked to objects in the virtual world in order to give each visual representation the necessary context [68].

A further aspect related to visual perception is the use of text, for example to label axes or items of the visual representations. In their recent study, Kruijff et al. [44] investigated different aspects of label design on search performance and noticeability in two experiments. One of their findings was that noticeability of motion differs between optical and video see-through displays, but using blue coloration is most noticeable in both.

In contrast to most of the work presented in the previous section that was targeting indoor use cases, the approaches presented in this section mostly concern outdoor use cases. A classic example of applying this approach is SiteLens by White and Feiner [94]. In their work, air quality measurements (non-volumetric, geo-spatially anchored data) are represented on a PDA (non-stereoscopic, spatially aware display) using 3D representation (see Figure 4.12).

The *FieldView* system, introduced by Whitlock et al. [95], brings together 2D mobile visualization on a non-stereoscopic device (smartphone, tablet) with a 3D

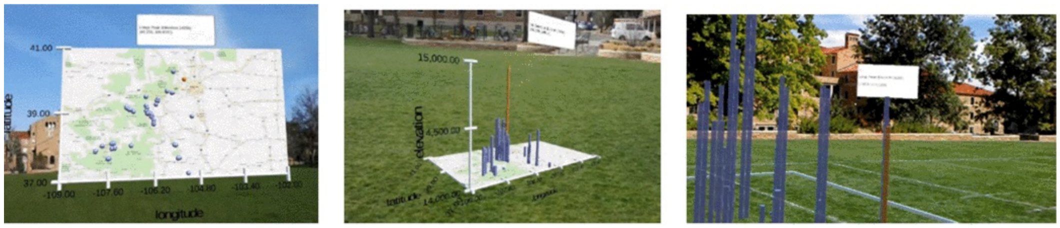


Figure 4.13: FieldView: Stereoscopic display of non-volumetric data using 3D representations. © *2020 IEEE. Reprinted, with permission, from [95].*

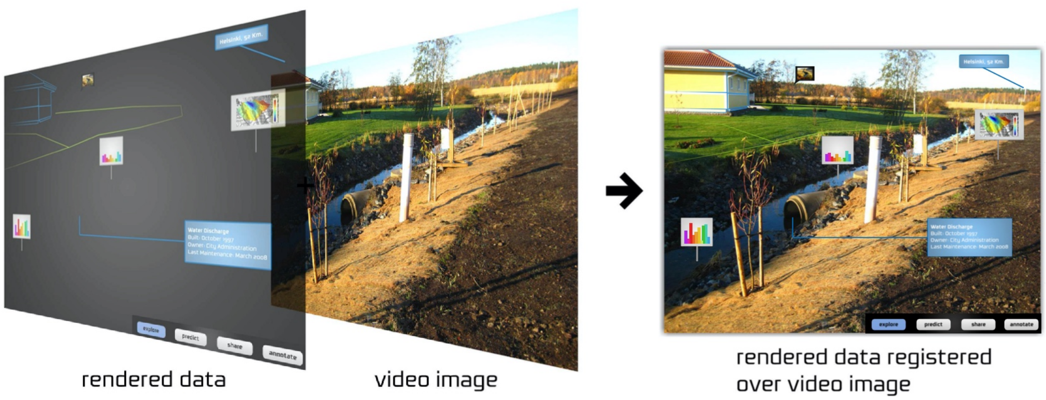


Figure 4.14: HYDROSYS: a project for on-site environmental monitoring that uses spatially aware 2D representations to display geo-spatially anchored data over a physical location [87]. *Image © Eduardo Veas, used with permission.*

representation on stereoscopic displays (AR headsets). Figure 4.13 shows three visualizations of the system *FieldView* using 3D representations of non-volumetric data. However, note that Figure 4.13 is an example of a non-spatially aware display albeit the data is geo-spatially anchored. In addition, the system is also capable of visualizing individual measurements in a spatially aware, stereoscopic representation, i. e., the visual elements representing measurements are positioned where they have been measured in real space.

2D representation on a stereoscopic display

Until now we have focused on employing the capability of stereoscopic environments to faithfully render data in 3D. What seems to be somewhat counter-intuitive is to use 2D representations in a stereoscopic context. Yet, there are also compelling use cases for this approach. First, stereoscopic displays like VR and AR headsets are capable of rendering 2D imagery on panels in the environment. This is particularly interesting when users cannot access classical workstations or analysis tools that Hybrid Virtual Environments (HVEs) usually provide. It becomes necessary when the data visualization supports work in a spatial context; for instance, workers have to repair or assemble in-situ within physical environments that cannot accommodate HVEs or when 2D visual representation have to be overlaid directly on physical elements. With this, workers wearing headsets can perform conventional 2D data visualization activities in unconventional environments. HYDROSYS [87] is an example of 2D representations in a spatially aware device. It overlays environmental monitoring data that is geo-spatially anchored over the real-world physical location of the measurement (see Figure 4.14). Extensions of this approach with area-based visual representations overlaid over the ground can be found in [86].

4.8 LESSONS LEARNED: COULD THE MARINES BE SAVED?

In the previous section, we have explored different ways to visualize 3D data with mobile devices and, for each configuration, we revisited our motivating example—the *Aliens* scenario. As simple as it seems, this scenario highlights some of the challenges that we have detailed in Section 4.5.

Being able to accurately visualize the 3D data of the aliens' position is of utmost importance to the survival of the marines. All investigated configurations can provide this, each of them with specific limitations which should be weighed based on the final use-case. Non-stereoscopic screens require us to design specific interaction mechanisms to allow the marines to easily navigate through the 2D slices of the representation of their spaceship. Spatially-aware handheld solutions are cumbersome and not ideal for collaborative analysis of data. Spatially-aware headsets leave the hands of users free but the virtual overlay can hide other relevant information. Eventually, the choice of a configuration over another will depend on the context and use-case. In the specific context of the *Aliens* scenario, mixed-reality headsets would probably be better suited for the marines. We therefore propose and illustrate (see Figure 4.15) a revised scenario in which the headsets are incorporated into the marines' helmets. Here is the synopsis:

> HICKS: Seal the door, hurry!
>
> *As in the original scenario, the team begins to barricade by welding the doors shut. However, now as soon the Aliens pass over the doors through the ceiling the marines become aware of the problem due to the signal from the tracker being directly overlaid on their helmet visors. They see the position of the aliens precisely in the context of the facility through a World-In-Miniature (WIM) view [81], they are also able to look up and see the Aliens approaching directly over the doors through an in-situ "x-ray vision" AR overlay.*
>
> HICKS: It's no use, they're coming through the ceiling.
>
> *Hudson and Vasquez begin accurately firing at the Aliens through the ceiling using this feature of their headsets, holding the advance at bay. Meanwhile, Ripley and Hicks continue using their shared WIM view of the facility plan to plot an escape route.*
>
> RIPLEY: We can get out this way!
>
> *Upon reaching safety, the marines are breathless and shaking with adrenaline.*

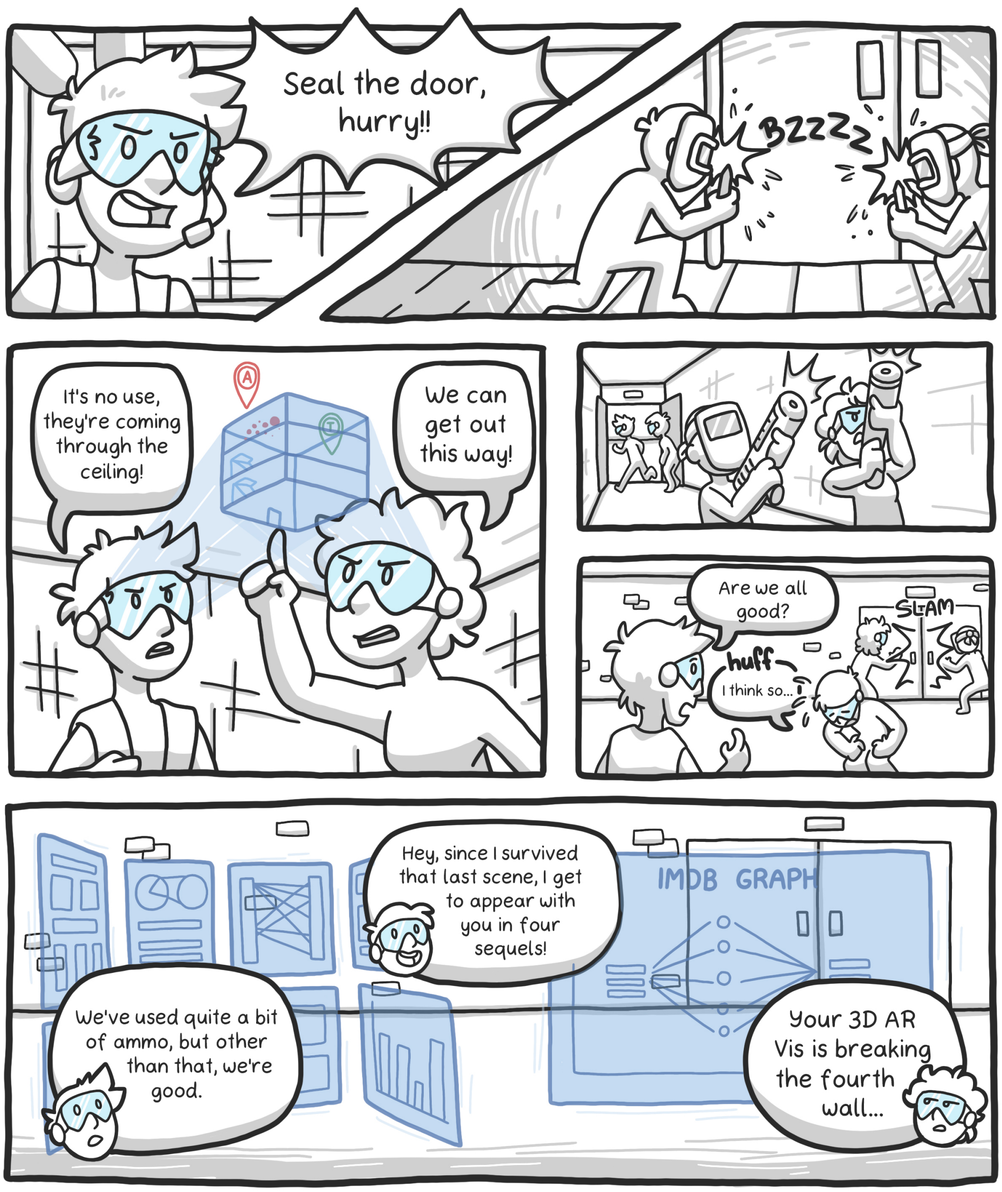


Figure 4.15: Reimagined scenario. *Image © Magdalena Boucher.*

HICKS: Are we all good?

HUDSON: I think so...

Hicks uses an AR small multiples view [48] of his team's vital statistics to confirm their status.

HICKS: We've used quite a bit of ammo, but other than that, we're good.

As his pulse rate returns to normal, Hudson's attention wanders from immediate concerns, to his next priority, life after The Corp. He begins to perform some abstract data visualization, browsing an immersive representation of actors and the films in which they appear on IMDB. He finds that Bill Paxton (not to be confused with proponent of sketching for user experience design, Bill Buxton [20]) appears in multiple films with Sigourney Weaver in the Aliens' franchise.

HUDSON: Hey, since I survived that last scene, I get to appear with you in four sequels!

RIPLEY: Your 3D AR Vis is breaking the fourth wall.

Fin.

In this revisited scenario, beyond the relatively simple task of locating the aliens, other challenges that we mentioned in Section 4.5 are also highlighted. Two of the marines collaborated to find an escape route, further highlighting the need to study co-located collaborative analysis and natural interactions techniques for immersive content. We can observe in this revised scenario that the model of spaceship is probably scaled from the first panel to the second one: to locate the aliens, the model is represented at scale and highlights the enemy's positions whereas when the marines are trying to plan an escape route, the model is scaled down to allow an overview of the spaceship. During all of this, it is obvious that the visual overlay provided by the headset should also be properly integrated with the marines' environment and not hinder their perception of critical objects, people, or aliens.

4.9 CONCLUSION

In this chapter, we have discussed scenarios that one might characterize as niche, workplace and domain specific examples. It therefore seems reasonable to wonder whether 3D mobile data visualization will become ubiquitous and, if so, when?

There is an argument that situated data visusalization can be useful in many real-world situations. While many of the examples above come from technical domains (e. g., engineering), the utility of receiving information about any object in the world that you look at, in the form of banners or other visual overlays hovering directly around that object, that may be transformational to engineers operating complex equipment, can be beneficial to people in their day-to-day lives also.

An obvious (but futuristic) example is technology supporting the party trick of low-key headsets (or implants?) reminding the wearer of the name of every person they encounter in a busy room, whether they have met them before or not. Names are just the beginning, with a lot of information already available in social-media services. Consider the implications for social engineering of reminding the wearer of their personal connection to every person they meet, or their tertiary connection via their social network. The physical world that we walk through can be overlaid with a "web" of connections that were previously invisible to show connections between people or objects, physically present or virtual. Managing the complexity of such virtual link overlays is a research challenge in itself [68].

Apart from social encounters 3D mobile visualization can usefully support people in their encounters with inanimate or electronic objects in their environment, just as it can support a facilities manager in a machine room. In the shopping center, people regularly are called upon to make complex purchasing decisions based upon all kinds of information that is not made obvious by a product's packaging. Examples include relating nutritional information to one's own dietary requirements, or the ethical or sustainability concerns related to a product that will certainly not be advertised by the manufacturer [30]. Some of these things can be achieved with today's handheld devices, for example with apps that can search for information about products based on images of their barcodes or packaging. However, hands-free, spatially aware headsets offer convenience as well as seamless, unobtrusive use that make them very attractive.

If 3D data visualization can assist or guide during design or engineering tasks, it is easy to imagine 3D mobile data visualization being used in situations where users' awareness and need for spatially-anchored information is crucial: driving while getting directions for instance. The superimposition of directions on the road and information that is necessary to safely drive a vehicle (other vehicle's speed or potential danger on the road) would be helpful in this task. Geo-spatially-anchored information would also help avoid the recurring last minute realization that, as a driver, we are in the wrong lane for a specific turn, or could help warn us about potential dead-angle dangers and therefore, not unlike our Alien scenario, potentially save lives. However, specific interaction techniques would have to be designed to best assist drivers whose hands are already taken by the car they are driving.

These scenarios quickly become data visualization challenges with a mix of complex abstract, quantitative and spatial information requiring effective representation in the space around the wearer of the device and the things they are looking at. While some of them seem far in the future, we already possess most of the technology to start solving the specific challenges they offer. One might therefore claim that 3D mobile data visualization will be ubiquitous, but the "when" is up to our ability to overcome remaining technological, social and organizational barriers to adoption.

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